RADIATION DOSIMETRY

RADIATION DOSIMETRY

This page intentionally left blank

RADIATION DOSIMETRY

Edited by

GERALD J. HINE
Veterans Administration Hospital
Boston, Massachusetts

and

GORDON L. BROWNELL
Massachusetts General Hospital
Boston, Massachusetts

1956

ACADEMIC PRESS INC. • PUBLISHERS • NEW YORK

COPYRIGHT© 1956 BY ACADEMIC PRESS INC.

ALL RIGHTS RESERVED

NO PART OF THIS BOOK MAY BE REPRODUCED IN ANY FORM
BY PHOTOSTAT, MICROFILM, OR ANY OTHER MEANS,
WITHOUT WRITTEN PERMISSION FROM THE PUBLISHERS

ACADEMIC PRESS INC.
111 FIFTH AVENUE
NEW YORK, NEW YORK 10003

United Kingdom Edition
Published by
ACADEMIC PRESS INC. (LONDON) LTD.
BERKELEY SQUARE HOUSE, LONDON W. 1

Library of Congress Catalog Card Number: 56-6605

First Printing, 1956
Second Printing, 1958
Third Printing, 1961
Fourth Printing, 1964
Fifth Printing, 1967

PRINTED IN THE UNITED STATES OF AMERICA

Contributors

H. O. ANGER, *Donner Laboratory and Radiation Laboratory, University of California, Berkeley, California*

E. A. BEMIS, JR., *Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico*

A. C. BIRGE, *Donner Laboratory of Biophysics and Medical Physics, University of California, Berkeley, California*

J. W. BOAG, *Medical College of St. Bartholomew's Hospital, London, England*[1]

G. L. BROWNELL, *Physics Research Laboratory, Massachusetts General Hospital, Boston, Massachusetts*

F. P. COWAN, *Health Physics Division, Brookhaven National Laboratory, Upton, New York*

R. A. DUDLEY, *Division of Biology and Medicine, U. S. Atomic Energy Commission, Washington, D. C.*[2]

S. GENNA, *Department of Physics, Memorial Center for Cancer and Allied Diseases, New York, New York*

G. J. HINE, *Radioisotope Service, Veterans Administration Hospital, Boston, Massachusetts*

J. G. HOLT, *Department of Radiology, City of Hope Medical Center, Duarte, California*

E. M. JAPHA, *X-Ray Department, Mount Sinai Hospital, Chicago, Illinois*

H. E. JOHNS, *Department of Physics, University of Saskatchewan, Saskatoon, Saskatchewan, Canada*[3]

J. S. LAUGHLIN, *Department of Physics, Sloan-Kettering Institute, Memorial Center for Cancer and Allied Diseases, New York, New York*

R. LOEVINGER, *The Andre Meyer Department of Physics, The Mt. Sinai Hospital, New York, New York*[4]

W. J. RAMM, *Signal Corps Engineering Laboratories, Ft. Monmouth, New Jersey*

L. L. ROBBINS, *Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts*

H. H. ROSSI, *Radiological Research Laboratory, Columbia University, New York, New York*

W. K. SINCLAIR, *Physics Department, University of Texas M. D. Anderson Hospital and Tumor Institute, Houston, Texas*

F. W. SPIERS, *Department of Medical Physics, The University of Leeds, Leeds, England*

G. V. TAPLIN, *Atomic Energy Project, University of California, Los Angeles, California*

C. A. TOBIAS, *Donner Laboratory and Radiation Laboratory, University of California, Berkeley, California*

C. C. WANG, *Massachusetts General Hospital and Harvard Medical School, Boston, Massachusetts*

---

[1] Present address: Radiobiology Research Unit, Mount Vernon Hospital, Northwood, Middlesex, England

[2] Present address: Radioactivity Center, Massachusetts Institute of Technology, Cambridge, Massachusetts

[3] Present address: Physics Division, Ontario Cancer Institute, Toronto, Ontario, Canada

[4] Present address: W. W. Hansen Laboratories of Physics, Stanford University, Stanford, California

This page intentionally left blank

PREFACE

Radiation dosimetry is concerned with the determination of the energy absorbed in a medium exposed to ionizing alpha- and beta-rays, electrons, and protons, and to ionizing secondary radiation produced by x-rays, gamma-rays, and neutrons.

In recent years problems of radiation dosimetry have multiplied rapidly with the vast production of artificial radioactive materials by reactors and the increasing use of high-voltage accelerators of various kinds. The energy ranges have been expanded considerably and electron, proton, and neutron beams find an increasing variety of important applications.

The continuing growth of radiation dosimetry and its extensive and widespread literature have created the need for an up-to-date and unified presentation of the significant aspects of the field. This book, written for those working with the applications of radiation to medical, industrial, and research problems, is designed to fill this need. The rapid growth of industrial power programs and technical uses of isotopes may well cause these applications to overshadow the medical uses in the future. The basic techniques of radiation dosimetry are the same in all these areas of research, and dosimetric problems of all kinds, including questions of health physics and personnel protection, can be solved by using the information and data presented here. The extensive references to the original literature will help the reader to find more specialized information if necessary.

The book is divided into three main parts. The first part presents the fundamental principles of dosimetry. In the first two chapters the concepts of dosimetry and the physical properties of radiation and their interaction with matter are discussed. In the third chapter, some of the basic biological and medical effects of radiation are presented to help the nonmedical reader understand the important medical implications of the radiations he is dealing with.

In the second part of the book the various instruments available for dosage measurements are described together with their uses for different types of radiation. This part includes information on scintillation detectors, photographic film, chemical and colorimetric indicators, and calorimetric methods, none of which have been extensively discussed previously from the viewpoint of their dosimetric applications.

The third part of the book presents the problems of dosimetry of various radiation fields. The chapter on x-rays is a thorough, modern review of a widely discussed subject. The chapters dealing with electron and proton beams open subjects which have rarely been dealt with before. The treatment of beta-ray dosimetry is perhaps the first comprehensive approach to this difficult field. No attempt has been made to treat ultraviolet and other kinds of nonionizing radiations.

When, three years ago, Academic Press suggested the organization of a book on radiation dosimetry it became immediately apparent that an up-to-date presentation of the intricate aspects of the field could be written only with the help of a number of specialists. The editors' problem was then to produce a cohesive textbook dealing with all aspects of radiation dosimetry and not merely to present a collection of specialized papers on various subjects related to dosimetry. Towards that end numerous drafts have been written and rewritten and some sacrifices have been made in the subject matter of various chapters. The editors assume complete responsibility for deletions and alterations made necessary by the desire to achieve an integrated presentation.

We wish to acknowledge the assistance given by Professor R. D. Evans who has served as advisory editor for this book. We are grateful for the encouragement given by Professors Failla, Gray, and others. Numerous reviewers have carefully read the various chapters, and their help and criticism is greatly appreciated. The subject index has been prepared by Mr. Richard McCall, and the figures have been redrafted by Mrs. Grace Rowe.

We would like to thank Dr. Belton Burrows of the Boston Veterans Administration Hospital and Dr. Walter Bauer of the Massachusetts General Hospital for their encouragement and permission to allot the necessary time to this project.

Boston, Massachusetts
March, 1956

GERALD J. HINE
GORDON L. BROWNELL

Note Added in Second Printing

The timely subject and the high standard of this book have yielded an undiminished demand which has exhausted its first printing in less than two years. Since its publication new knowledge of an increasing number of subjects on radiation dosimetry has become available in addition to those presented here. However, with the exception of a few minor points, none of the material described in this book seems to require any basic revision. Therefore, new topics will be presented in future supplements rather than in a new edition of the complete volume.

Those errors and misprints which have been brought to the attention of the Editors have been corrected in the second printing. Furthermore, at the end of Chapter 9, a short section has been added; Fig. 11 on page 616 has been replaced by a corrected one; and Table I and Table II of the appendix have been brought up to date and some radioisotopes have been added to Table II.

Boston, Massachusetts
March, 1958

GERALD J. HINE
GORDON L. BROWNELL

CONTENTS

List of Contributors v
Preface vii

FUNDAMENTAL PRINCIPLES OF DOSIMETRY

1. Radiation Units and Theory of Ionization Dosimetry. By F. W. Spiers
I. Introduction 1
II. Units of Dose 7
III. Quantities Derivable from the Roentgen 12
IV. Determination of Dose in Roentgens 18
V. The Bragg-Gray Theory of the Small Ionization Chamber 23
VI. Ionization Dosimetry of High-Energy Photons and Corpuscular Radiations 39
References 44

2. Interaction of Radiation with Matter. By H. E. Johns and J. S. Laughlin
I. Electromagnetic Radiation 10^3 to 10^8 Electron Volts 50
II. Electrons 95
III. Neutrons 108
IV. Heavy Charged Particles 114
References 121

3. Biological and Medical Effects of Radiation. By C. C. Wang and L. L. Robbins
I. Mechanism of Radiation Effects on Living Cells 126
II. Effects of Radiation in General 128
III. Biological Effect of Radiation on Normal Tissues 131
IV. Radiation Effects on Malignant Tissues 141
V. Levels of Radiation 144
References 149

RADIATION DETECTORS AND THEIR CALIBRATION

4. Ionization Chambers. By J. W. Boag
I. Introduction 153
II. The Design of Ionization Chambers 154
III. Special Types of Ionization Chambers 198
References 210

5. Geiger-Mueller Counters and Proportional Counters. By Warren K. Sinclair
I. Introduction 214
II. Physics of Counters 214
III. The Use of Counters for the Dosimetry of Radioactive Isotopes 234
IV. The Use of Counters for the Measurement of Radiation Fields 238
References 242

6. Scintillation Detectors. By Wolfgang J. Ramm
I. Physics of Scintillation Detectors 246
II. Scintillating Materials and Their Light Yield 250
III. Scintillation Detector Dosimetry of X- and γ-Rays 259

IV. Scintillation Detector Dosimetry of Charged Particles 281
V. Scintillation Detector Dosimetry of Neutrons 289
References 297

7. Photographic Film Dosimetry. By Robert A. Dudley
I. Physics of Film Dosimetry 300
II. Calibration and Standardization Techniques 339
III. Instrumentation 346
IV. Applications 352
References 353

8. Chemical and Colorimetric Indicators. By George V. Taplin
I. Introduction 358
II. Physics of Chemical Dosimeter Systems 361
III. Dosimetry with Liquid Chemical Systems 368
IV. Applications of Chemical Dosimeters 386
V. Synopsis of Chemical Methods for Dosimetry of X-, γ-, and Fast Neutron Radiation 405
References 408

9. Calorimetric Methods. By J. S. Laughlin and S. Genna
I. Introduction 411
II. Principles of Calorimetry 413
III. Heat Detection 423
IV. Calorimetric Determinations of Quantity of Radiation 436
V. Absorbed Dose Measurements 445
VI. Source Strength Calibration 449
VII. Local Absorbed Dose Calorimeter 451
References 452

10. Survey Instruments and Pocket Dosimeters. By Edwin A. Bemis, Jr.
I. Introduction 454
II. Gamma-Ray Instruments and Dosimeters 459
III. Beta-Ray Instruments and Dosimeters 471
IV. Alpha-Ray Instruments and Dosimeters 473
V. Neutron Instruments and Dosimeters 475
VI. Film Badges 482
VII. Air Monitoring 490
VIII. Calibration Techniques 495
IX. Civil Defense Instruments 498
X. Future Trends 500
References 501

11. Standardization of X-Ray Beams and Radioactive Isotopes. By Warren K. Sinclair
I. Standardization of X-Ray Beams and Radium 506
II. Standardization of Radioactive Isotopes 509
References 528

RADIATION FIELDS AND THEIR DOSIMETRY

12. X-Rays and Teleisotope γ-Rays. By H. E. Johns
I. Production of Radiation 532
II. Surface Backscatter 546
III. Percentage Depth Dose 551
IV. Isodose Distributions of Radiation 562

V. Rotation Therapy ... 565
VI. Clinical Radiation Distributions ... 569
VII. Integral Dose and Energy Absorption ... 577
VIII. Spectral Distribution of Radiation ... 586
References ... 594

13. High-Energy Electron Beams. By John S. Laughlin
I. Sources of High-Energy Electrons ... 597
II. Intensity Measurements ... 603
III. Dose Measurements ... 607
IV. Electron Beam Applications ... 618
References ... 619

14. Heavy Charged-Particle Beams. By Ann C. Birge, Hal O. Anger, and Cornelius A. Tobias
I. Introduction ... 624
II. Physical Properties of Heavy Charged Particles ... 624
III. Dose Measurement ... 641
IV. Applications ... 660
References ... 662

15. Neutrons and Mixed Radiations. By Harald H. Rossi
I. Introduction ... 667
II. Theoretical Neutron Dosimetry ... 673
III. Methods of Experimental Neutron Dosimetry ... 677
IV. Dose Measurements in Mixed Radiation Fields Containing Neutrons of Various Energies ... 685
V. Neutron Capture Therapy ... 689
References ... 690

16. Discrete Radioisotope Sources. By R. Loevinger, E. M. Japha, and G. L. Brownell
I. Beta-Radiation ... 694
II. Gamma-Radiation ... 754
References ... 794

17. Internally Administered Radioisotopes. By R. Loevinger, J. G. Holt, and G. J. Hine
I. Physical and Biological Factors Controlling Concentration of Administered Isotopes in Tissue ... 803
II. Beta-Particle Dosimetry ... 823
III. Gamma-Ray Dosimetry ... 850
IV. Examples of Tissue Dose Calculations ... 862
References ... 871

18. Isotope Shipment and Disposal. By F. P. Cowan
I. Shipment of Radioactive Isotopes ... 876
II. Disposal of Radioactive Wastes ... 878
References ... 892

Appendix: Tables of Data Useful for Dose Calculations. By Gerald J. Hine 897

Author Index ... 909

Subject Index ... 925

Figures Containing Data Directly Applicable to Dose Determinations

PAGE

Mass absorption coefficients for air as a function of photon energy 82

Mass absorption coefficients for water as a function of photon energy 83

Mass absorption coefficients for lead as a function of photon energy 85

Energy absorbed per gram-roentgen for bone, muscle, fat, and air as a function of the photon energy 90

Threshold erythema dose as a function of roentgen-ray peak voltage 132

Ionization current as a function of dose rate and chamber volume 193

Variation of the x-ray backscatter factor with the quality of radiation for a number of field sizes 550

Percentage depth dose for five types of x-radiation as a function of depth 552

Integral dose for the same tumor dose as a function of patient thickness for 200 kv, Co^{60}, and betatron radiation 582

Theoretical depth dose curves for monoenergetic neutron beams incident on a 30 cm slab of tissue 677

Average β-ray energy of allowed spectra 698

Depth dose distribution from a thin source of P^{32} β-particles 730

Central-axis depth dose curves of plane β-ray applicators 751

Gamma-ray dose-rate constant, Γ, for a γ-ray point source in air as a function of the γ-ray energy, E_γ 757

Radium exposure (mg-hr) to produce 1000 r as a function of the treatment area and the source to treatment area distance 787

Variation of the γ-ray dose rate inside and outside a sphere containing a uniform distribution of a γ-ray-emitting radioisotope 855

Tables of Data Directly Applicable to Dose Determinations

	Page
Relative biological effectiveness and specific ionization	11
Energy flux per roentgen and energy absorption by biological material	88
Radiation dosimetry and biological response	147
X-rays: backscatter factors for circular fields	551
Depth dose data for low-energy x-rays	558
Depth dose data for medium-energy x-rays and Co^{60} γ-rays	559–562
Tumor-air ratios for circular x-ray fields	566
Tumor-air ratios for rectangular x-ray fields	568
Gamma-ray dose build-up factor for point source in infinite absorbing media	774
Quimby table for γ-ray dosage for external radium sources	792
Quimby table for γ-ray dosage from interstitial sources	793
Ranges of β-particles	878
Isotope decay chart	880–881
Maximum permissible concentrations of radioactive contaminants in water	883
Radiological data of frequently used radioisotopes	899
Radiological data of other radioisotopes, the decay schemes of which are fairly well established	903
Biological properties of some radioisotopes administered to human beings	906
Some characteristics of the standard man. (1) Mass of organs of the standard, adult human body. (2) Chemical composition, adult human body	907

Abbreviations of Names of Reports

AECU—Atomic Energy Commission Unclassified

AECD—Atomic Energy Commission Declassified

AERE T/R—Atomic Energy Research Establishment, Harwell, England

ALI—A. D. Little Company

ANL—Argonne National Laboratory

ARSC—Air Reduction Company

BNL—Brookhaven National Laboratory

BR—British Reports

CRM—Atomic Energy Project (Chalk River, Canada)

DP—E. I. du Pont de Nemours and Co.

HW—Hanford Works, General Electric Co.

IDO—Idaho Operations Office

JHUX—Johns Hopkins University

JHUL—Johns Hopkins University

KLX—Vitro Corporation of America

KAPL—Knolls Atomic Power Laboratory (General Electric Co.)

LA—Los Alamos Scientific Laboratory (University of California)

MDDC—Manhattan Engineer District and AEC declassified

NBS—National Bureau of Standards

NPL—National Physical Laboratory, England

NYO—New York Operations Office AEC

NP—Non project report

ONRL—Office of Naval Research (London)

ORNL—Oak Ridge National Laboratory

TOI—Technical Operations Inc.

TID—Technical Information Service, AEC

UCRL—University of California Radiation Laboratory

UR—University of Rochester Atomic Energy Project

UCLA—University of California at Los Angeles Atomic Energy Project

WASH—Atomic Energy Commission, Washington

CHAPTER 1

RADIATION UNITS AND THEORY OF IONIZATION DOSIMETRY

F. W. Spiers

I. Introduction 1
A. Types of Ionizing Radiation 2
B. Physical Quality and Intensity 3
C. Concept of Radiation Dose 5
D. Ionization and Energy Absorption 6
II. Units of Dose 7
A. The Roentgen 7
B. The Intermediate Units 8
1. The Gram-Roentgen 8
2. The Roentgen-Equivalent-Physical (rep) 9
3. The Energy Unit 9
4. The Roentgen-Equivalent-Man (rem) 10
C. The New Units 10
III. Quantities Derivable from the Roentgen 12
A. Energy Absorption in Air 12
B. Energy Flux in Air for Given Quantum Energy 12
C. Energy Absorption in Other Media 13
IV. Determination of Dose in Roentgens 18
A. Conditions of Ionization Current Measurement 18
B. Parallel-Plate Ionization Chamber for Low- and Medium-Energy X-Rays 19
C. High-Pressure Parallel-Plate Chamber for High-Energy X- and γ-Rays 22
V. The Bragg-Gray Theory of the Small Ionization Chamber 23
A. Statement of Fundamental Theory 23
B. Elaboration of the Cavity Ionization Chamber Theory 26
C. Calculation of Stopping Powers 27
D. Effective Stopping Power Ratio 29
E. Energy Spectrum of Electrons 34
F. Energy Loss (W) per Ion Pair 37
VI. Ionization Dosimetry of High-Energy Photons and Corpuscular Radiations 39
A. Quantum Radiation above 3 Mev 40
B. Beta-Radiation 42
C. Neutrons 43

I. INTRODUCTION

The subject of radiation dosimetry has its origins in the last years of the nineteenth century when x-rays, then newly discovered, were put to almost

immediate medical use. Both the successes, like that of the first recorded tumor treatment in 1899, and the failures of those early attempts underlined the necessity for some quantitative measurement of the radiations emanating from an x-ray tube. Most of the early workers used photographic or fluorescence methods for measuring x-ray intensities; but it is of interest that chemical methods were tried and also that as early as 1897 a measurement was made of the heat produced by the complete absorption of an x-ray beam in a metal. For reasons of lack of sensitivity, of unreliability, or of unwanted quality dependence, these early physical techniques were eventually displaced by ionization methods; but three decades passed before an internationally acceptable method of defining and measuring an x-ray dose was achieved. The introduction of the roentgen in 1928 likewise turned attention away from use of biological indicators, which by their nature inevitably lacked the precision of physical measurements.

The problem today is no longer solely that of standardizing dose in the medical use of x-rays and radium γ-rays. The advance of nuclear science and the now-abundant production of radioactive materials pose the problems of dosimetry in new and complicated forms. More than ever it is necessary to determine the *physical energy deposition* in a variety of media when irradiated by any one of a wide energy range of quanta or by any type of ionizing particle. Modern versions of some of the earlier methods, notably chemical (Chapter 8) and calorimetric (Chapter 9) methods, are gaining an important place in radiation dosimetry. At first, however, the fundamental concept of radiation dose and the extent to which it has been satisfactorily measured by ionization methods has to be considered.

A. Types of Ionizing Radiation

Some indication of the extent and nature of the problem of radiation dosimetry is apparent from the great variety of the ionizing radiations which are now available. Table I gives a list of commonly used radiations, their energies, and the approximate average range, in low atomic number material, of the associated ionizing particle. Electromagnetic radiations, having energies above a few kev, ionize by virtue of the secondary electrons released when they are absorbed. Corpuscular radiations ionize either directly, because they are charged, or indirectly through charged particles set in motion by collision processes.

The ionizing particles have complex energy spectra, and hence only the order of the mean range is given in Table I. In biological materials which have nearly unit density the range can vary from about 1 micron to a few centimeters, or even to as much as 1 meter in the case of very-high-energy protons. The magnitude of the range in relation to the size of the biological entity is fundamental to the problem of determining the energy deposition

TABLE I

TYPES OF IONIZING RADIATION

Radiation	Energy range, Mev	Ionizing particle in tissue	Average range of ionizing particle in low atomic number material	
			gm/cm²	cm of air at STP
1. β-rays	0.015–5	Electron	10^{-4}–1.0	0.1–800
2. Electron beams	2–20	Electron	1–10	800–8000
3. γ-rays	0.05–2.9	Electron	5×10^{-4}–0.6	0.4–450
4. X-rays	0.01–0.4	Electron	10^{-4}–5×10^{-3}	0.1–4
5. X-rays	1–10	Electron	5×10^{-2}–1.2	30–230
6. X-rays	10–30	Electron	1.2–3.5	1500–2700
7. Fast neutrons	0.1–10	Proton	10^{-4}–6×10^{-2}	0.1–45
8. Slow neutrons	0.1 ev	0.6-Mev protons (+2.2-Mev γ-rays)	10^{-3} (protons) 0.5 (electrons)	0.8 (protons) 400 (electrons)
9. Proton beams	5–400	Proton	3×10^{-2}–10^{2}	$23–8 \times 10^{4}$
10. α-rays	5–10	α-particle	3×10^{-3}–10^{-2}	2–8

in irradiated organisms. Likewise the particle range in air or other gases is a major consideration in the practical realization of the theory of ionization dosimetry. Although detailed consideration will follow later in this and other chapters, it may be noted that air-ionization methods are applicable where the same type of ionizing particle is released in the ionization chamber and in tissue. Where this is not so, as in the case of neutrons and high-energy protons, both the walls of the ionization chamber and the gas filling must simulate tissue in atomic composition, especially in respect to the hydrogen content (see Chapter 15). Further considerations are necessary when more than one type of radiation is present and where nuclear reactions occur.

B. Physical Quality and Intensity

For many purposes an exact specification of radiation *quality* is not necessary. In therapeutic x-ray work, for example, a sufficient indication of the quality of the radiation is given by a simple function of the penetration of the beam. The function frequently employed is the *half-value layer* (HVL), defined as the amount of some standard material which transmits 50% of of the incident radiation. The half-value layer can be used further to specify an *effective wavelength* or *effective energy* as that wavelength or energy of a monoenergetic radiation which exhibits the same half-value layer as the heterogeneous beam in question. The only complete specification of the physical quality of a radiation, however, is the spectral distribution of wavelengths or energies present (Chapter 2). In its most useful form, the dis-

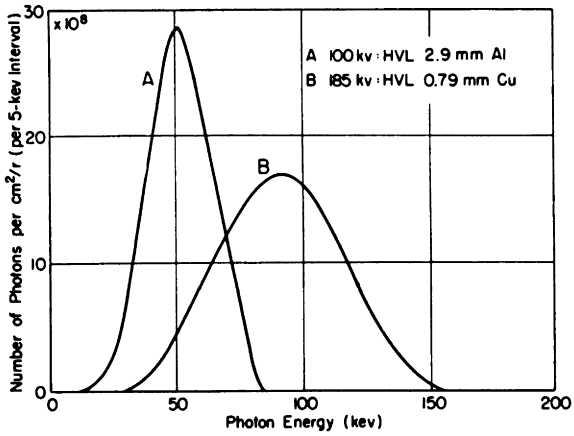

FIG. 1. Photon spectra deduced from absorption data. The mean energies of radiations *A* and *B* are, respectively, 52 kev and 90 kev. The effective energies derived from the stated half-value layers are 34 kev and 71 kev, respectively.

tribution, showing the number of photons in each energy interval, enables calculation to be made of the numbers and energies of the secondary ionizing particles released in tissues or other media, when these are needed for purposes of dosimetry or for the interpretation of chemical and biological effects. The effective energy of the beam derived simply from the half-value layer does not necessarily coincide with the mean energy more correctly deduced from the photon spectrum. Methods of specifying the effective energies of heterogeneous radiations should be carefully scrutinized if they are being used to correlate possible energy-dependent phenomena. The photon spectra in Fig. 1, which have been deduced from absorption data by a method described in Chapter 2, illustrate the points discussed. The effective energies derived from the half-value layers are 34 kev and 71 kev for radiations which have mean energies of 52 kev and 90 kev, respectively. Deductions from the single absorption measurement of the half-value layer underestimate the mean energy of the radiation.

The methods of radiation spectroscopy are dealt with in Chapter 2; here it should be noted that where quality dependence is being investigated the complete energy spectrum of the radiation has to be determined.

The *intensity* of electromagnetic radiation at any point is defined in its precise sense as the radiation energy in ergs flowing per second through 1 cm^2 of area perpendicular to the direction of propagation (40). The radiation at a given point is completely specified, therefore, if the photon energy spectrum and the energy flux are known.

An equivalent and sometimes useful specification is the statement of the photon energy spectrum and the photon flux, i.e., the number and energy

of photons flowing per second through 1 cm^2 perpendicular to the incident direction. The relationship of the energy flux to the rate of energy absorption in any particular physical or biological system depends primarily on the photon energy. Because the detection and measurement of any radiation necessarily involves energy absorption by the measuring system, intensity measurements and dose or dose-rate measurements will be seen to present very similar problems. The ease or difficulty with which they can be solved depends in a like manner on the radiation quality.

C. Concept of Radiation Dose

It may be regarded as axiomatic that radiation can bring about a change in a system only by virtue of the *energy* actually *absorbed.* A biological effect, however, may also depend on the spatial distribution of the energy released along the track of the ionizing particle. It will depend, therefore, on the type and quality of the radiation, and equal energy absorptions of different radiations may not produce equal biological effects. These features of the action of ionizing radiations on living cells are illustrated in Fig. 2, where the relative biological effect of a given energy absorption is shown to vary markedly with the density of ion formation along the track of the ionizing particle (33, 59). Generally, the effect of radiation on cell structures increases with increase in linear ion density, but certain "all or none" actions, like the inactivation of bacteria and viruses, become less efficient

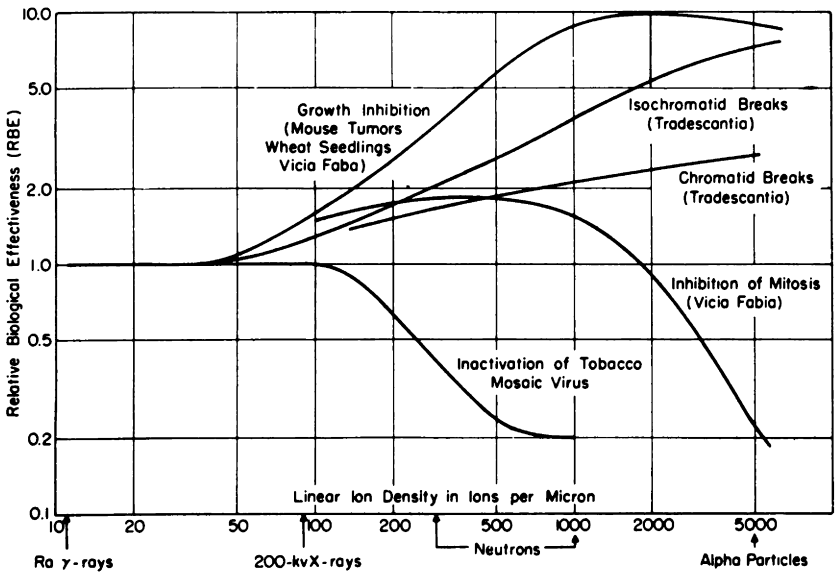

FIG. 2. Variation of relative biological effectiveness (RBE) with linear ion density for a number of radiobiological actions (33, 59).

per unit energy absorption at the higher ion densities. Moreover, different biological actions vary in the manner of their dependence on radiation quality. For this reason, the concept of "dose," in terms of a defined reaction of some standard biological indicator, does not avoid the difficulty that doses of different radiations, which are equal in the defining system, may produce unequal reactions in other systems. It is preferable, therefore, to define "dose" in physical terms and to use another factor to allow for the "relative biological effectiveness" (RBE) of different types and quality of radiation (Fig. 2). Since any consideration of the primary physical action of ionizing radiation must be based on energy absorption, the fundamental concept of *physical dose is the energy absorbed in ergs per gram* of the irradiated material. It is this concept of dose and its practical realization that will underly the discussions in this chapter and in those which follow.

In the case of some radiations, such as ultraviolet rays and very soft x-rays, the whole of the incident energy may be absorbed in the biological system concerned. The time integral of the radiation intensity is then identical with the total energy absorbed. For penetrating radiation this simplification no longer holds. When x- and γ-rays traverse matter, the photon energy may be transferred partly or wholly to an electron which is then set in motion with an energy usually greatly in excess of its binding energy in the atom or molecule. Compared with the photon, this projected electron has a small range in liquids and solids. Therefore, except in those cases where the range is comparable to the size of the structure concerned or where radiation losses are important, the electron dissipates all its energy in the medium in which it arises. The radiation energy thus transformed into kinetic energy of secondary electrons is referred to as the *real* or *true energy absorption*. Because usually only a fraction of the incident radiation energy is given up to the medium, this concept of dose is not the same as the time integral of the radiation intensity and, of course, the term "dose rate" is not synonymous with physical intensity. Sometimes, however, the dose rate of an irradiation is loosely called "intensity," but in this context the latter term means dose rate or rate of energy absorption, not rate of energy incidence.

D. Ionization and Energy Absorption

The energy acquired by the secondary electron by the absorption of an x- or γ-ray is dissipated in the medium chiefly by collision losses resulting in ionization and excitation of the molecules involved. Only at high electron energies (5 Mev upward) does the radiative energy loss by electrons become appreciable (Chapter 2). In aqueous media it may be inferred (35) that the energy expended by a secondary electron in collision processes is roughly equally divided between ionization and excitation. These two forms of

energy dissipation, however, may not be equal in their chemical or biological action. In view of the low efficiency of excitation processes in the inactivation of viruses and bacteria by ultraviolet light, Lea (59) concluded that the biological effects of ionizing radiations were almost entirely due to ionization. Gray has also produced some evidence that in water irradiated by electrons the energy of excitation not used in causing molecular dissociation is degraded below quantum energies of the order of 1 ev, that is, below energies which are chemically or biologically effective. More knowledge of ionization and excitation processes in liquids is required before their relative importance in biological and chemical actions can be assessed. Irrespective of such considerations, however, dosimetry in terms of the *total energy absorbed* by the irradiated material is justified because it gives the physical information on which any further analysis must be based.

Because of the great difficulties of measuring small increments of energy by thermal means, calorimetric dosimetry has only in recent years become a realizable method (Chapter 9). The principal method of dosimetry has been based on the ionization of gases, usually of air. Although air ionization affords only an indirect measure of energy absorption in other media, it has proved to be of the greatest value in medical radiology and is likely to remain the method of choice for many dosimetric problems. Since air and soft tissues are composed mainly of elements of low atomic number, the "effective atomic number" of air (however the average is taken) is not very different from that of human tissue or of water. The absorption of ionizing radiations per gram of air is then nearly the same as that in tissue or water over a considerable range of radiation energies, and the resulting ionization in air offers an accurate and adaptable electrical method of dosimetry. The acceptance of air ionization as the means of defining and measuring an x-ray dose was to a large extent due to the practicability of the method and to the fact that it measured energy absorption, although not in tissue, in an approximately "tissue-equivalent" material.

II. UNITS OF DOSE

A. The Roentgen

The international unit of x-ray dose was originally defined at the Stockholm Congress of Radiology (1928) as follows:

"The roentgen is the quantity of x-radiation which, when the secondary electrons are fully utilized and the wall effect of the chamber is avoided, produces in 1 cm^3 of atmospheric air at 0°C and 76 cm of mercury pressure such a degree of conductivity that 1 esu of charge is measured at saturation current."

This definition of the roentgen, which is also a prescription for its measurement, was modified at the Chicago Congress of Radiology (1937) to a form applicable also to the dosimetry of radium γ-rays. The changed

wording, which is still current, reads:

"The roentgen shall be the quantity of x- or γ-radiation such that the associated corpuscular emission per 0.001293 gm of air produces, in air, ions carrying 1 esu of quantity of electricity of either sign."

Both forms of wording have left room for discussion as to the precise quantity which the roentgen is intended to define. Some hold that, in specifying "the quantity of x-radiation which . . . *produces*" the effect measured, the first form defines the quantity of *absorbed* radiation in a given mass of air, and that similarly the corpuscular emission of the second definition is associated with the absorbed radiation. On the other hand, it can be equally well maintained that the corpuscular emission is associated with the incident radiation flux and that the roentgen is therefore a partial definition of the time integral of the incident radiation intensity. What is perhaps most significant is that an amount of ionization is defined which, in fact, implies an energy absorption per unit mass of air which is almost invariant with photon energy. Fortunately the energy-absorption aspect of the roentgen has been very much in the minds of radiation physicists and radiobiologists, and in practice the unit has been used with less ambiguity than its definition might lead one to fear. (At the risk of emphasizing the obvious, it should be stated that, since the unit is essentially related to energy absorbed, it is fallacious to multiply the dose in roentgens by an absorption coefficient to obtain an energy absorption.)

It is hardly to be expected that the roentgen could apply without qualification to the whole range of quantum and corpuscular radiations now available. The validity of the roentgen becomes questionable when the secondary corpuscular emission is not in equilibrium with the primary quantum radiation. For example, the roentgen is inadequate as a statement of the dose at an air-tissue interface, such as the skin, where a finite depth must be reached before secondary electronic equilibrium is attained. The difference between the true energy absorption in the surface tissue and that implied by the roentgen dose is unimportant for x-rays generated at potentials up to a few hundred kilovolts but becomes one of considerable magnitude in the case of high-energy radiations. In order to avoid such difficulties and to bring corpuscular radiation dose under one and the same definition, a number of units were proposed, all expressed essentially in terms of energy absorption without necessarily specifying the type of radiation producing it.

B. The Intermediate Units

1. The Gram-Roentgen

In order to express the total energy absorbed throughout a volume of irradiated tissue in terms of a unit related to the roentgen, Mayneord (68)

defined a *gram-roentgen* as equal to the x- or γ-ray energy absorbed when 1 gm of air is exposed to 1 r. It will be calculated in Section III that the value of the gram-roentgen is approximately 84 ergs and is almost independent of the radiation quality. The energy absorption when 1 r is received by 1 gm of aqueous tissue is greater than this, since the mass absorption coefficients of tissue and air are not identical.

2. The Roentgen-Equivalent-Physical (rep)

By definition the roentgen is unsuitable for expressing dose in the case of *corpuscular* radiations. Accordingly Parker (72) suggested another unit, the *roentgen-equivalent-physical* (*rep*), defined as "that dose of ionizing radiation which produces an energy absorption of 84 ergs/cm^3 in tissue." This value was originally chosen to be the same as the energy absorption per roentgen per gram of air and was not identical, therefore, with energy absorption per roentgen in tissues, since this depends on both tissue composition and radiation quality. Later the value of the rep was changed to 93 ergs/cm^3 of tissue, because this figure represents more accurately the energy absorption per cubic centimeter of aqueous tissue which has received a dose of 1 r of hard x-rays or γ-rays. This correspondence between the rep and the roentgen holds only for aqueous tissues and for quantum energies at which neither photoelectric absorption nor pair production is important. In contrast to the roentgen, the rep specifies a *fixed energy absorption per cubic centimeter of tissue*, irrespective of tissue composition or type of ionizing radiation. The rep is sometimes expressed, however, in terms of energy absorption per gram of tissue and is applied in this sense to dosage in tissues of density differing from unity, e.g., in bone. It is unfortunate that this unit has changed its value and appeared in the literature variously as energy absorbed per unit volume or per unit mass. Nevertheless, its use has represented a step in the direction of defining dose simply in terms of a fixed absorption per unit mass of irradiated material.

3. The Energy Unit

In proposing a unit which would correspond to the energy value of the roentgen for γ-rays, Gray and Read (30) defined an *energy unit* as that dose delivered to tissue by ionizing radiation such that the energy absorbed per gram of tissue is equal to the energy absorbed per gram of water exposed to 1 r of γ-radiation. For γ-ray energies in the 1- to 2-Mev range, the roentgen, the later definition of the rep, and the energy unit all imply the same energy absorption of approximately 93 ergs/gm of soft tissue. At other quantum energies the rep and the energy unit no longer correspond to the energy absorption per roentgen in soft tissue. They are applicable, however, to any type of quantum or corpuscular radiation, and they imply a fixed energy absorption per gram of tissue.

4. The Roentgen-Equivalent-Man (rem)

The *roentgen-equivalent-man* (*rem*) was defined (72) originally as the dose which, delivered to man (or mammal) exposed to any ionizing radiation, is biologically equivalent to the dose of 1 r of x- or γ-radiation (not photoelectrically absorbed). The rem is thus intended to take into account the relative biological effectiveness (RBE) of different types of radiation. Such factors, however, vary not only with the properties of the radiation but also with the biological effect studied (Fig. 2). It became customary, therefore, to regard the rem as a "biological" unit of dose defined by the relation:

$$\text{Dose in rem} = \text{Dose in rep} \times \text{RBE} \tag{1}$$

where for a given biological action the RBE values are stated as inverse ratios of the energy absorptions of different radiations which produce equal biological effects.

C. The New Units

The International Commission on Radiological Units (40), meeting in Copenhagen in July 1953, made recommendations which, in so far as they relate to definitions of units, are summarized below:

1. *Intensity of radiation* is defined in the strict sense already given in Section I-B. It is the energy flowing through unit area perpendicular to the beam per unit time and is expressed in ergs/cm^2-sec.

2. *Quantity of radiation* is defined as the time integral of the radiation intensity. It is the total energy which has passed through unit area perpendicular to the beam and is expressed in ergs/cm^2.

3. *Absorbed dose* is defined as the amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. It is expressed in *rads*. The rad is then defined as the unit of absorbed dose and is 100 ergs/gm. It should be noted that no definition of "dose" was agreed on, so the term "absorbed dose" is the only one that has a precise meaning.

4. *Integral absorbed dose* is defined as the integration of the energy absorbed throughout a given region of interest and is expressed in *gram-rads* 1 gm-rad being 100 ergs.

5. The *roentgen* retains the same definition as in 1937 and remains the unit of x- and γ-ray dose up to quantum energies of 3 Mev.

6. The *rem* is not officially listed as a unit, but in the recommendations of the International Commission on Radiological Protection (41) it is suggested that this unit should be used when it is necessary to add the doses of different radiations received. The rem is then defined in relation to the rad:

$$\text{Dose in rem} = \text{Dose in rad} \times \text{RBE} \tag{2}$$

TABLE II

RELATIVE BIOLOGICAL EFFECTIVENESS AND SPECIFIC IONIZATION (41)

Average specific ionization, ion pairs/μ in water	Average linear energy transfer, kev/μ in water	RBE
100 or less	3.5 or less	1
100–200	3.5–7.0	1–2
200–650	7.0–23	2–5
650–1500	23–53	5–10
1500–5000	53–175	10–20

RELATIVE BIOLOGICAL EFFECTIVENESS AND TYPE OF RADIATION (41)

Radiation	Biological effect	RBE
X-rays, γ-rays, and electrons and β-rays of all energies	Whole-body irradiation (blood-forming organs critical)	1.0
Fast neutrons and protons up to 10 Mev	Whole-body irradiation (cataract formation critical)	10
Naturally occurring α-particles	Carcinogenesis	10*
Heavy recoil nuclei	Cataract formation	20

* If direct comparison with body burden of 0.1 μc of radium is not possible.

7. The same committee (41) has recommended values of RBE to cover all ionizing radiations; these are listed in Table II.

It will be observed that, in the new recommendations, the rad refers to *absorbed dose* and the word *dose* appears only in conjunction with the definition of the roentgen, which is retained on practical grounds for use up to photon energies of 3 Mev. A dose of 1 r implies an absorbed dose of about 93 ergs/gm of soft tissue, or 0.93 rad in the range of photon energies from 0.3 to 3 Mev; but the precise value of the energy absorption depends on tissue composition and, in the lower photon energy range, on the radiation quality. The rep (second definition) and the energy unit, however, are both equivalent to 0.93 rad independently of radiation type and tissue composition. The unit of *integral dose*, the gram-roentgen, is equivalent to 84 ergs or 0.84 gm-rad in air, but the equivalent energy absorption in tissues will depend on tissue composition and radiation energy.

It appears to the writer that, although necessary in the present circumstances, the use of the term "absorbed dose" is in some ways an expedient and that the concept "dose," applied to radiation, should mean simply and only the energy absorption in suitable units per gram of material irradiated. It may well be, however, that time and use will establish the rad as the unit employed for all radiations and the distinction now made between dose in roentgens and absorbed dose in rads will no longer be necessary.

III. QUANTITIES DERIVABLE FROM THE ROENTGEN

A. Energy Absorption in Air

By definition of the roentgen, the charge released by the associated corpuscular emission per 0.001293 gm of air is 1 esu. The number of ion pairs produced by the energy absorption in 0.001293 gm of air is, therefore, $1/e$, where e is the electronic charge in electrostatic units. If W is the energy lost by a secondary electron per ion pair formed in air, the energy represented by this number of ion pairs is W/e.

Discussion of the precise value of W will follow in Section V-F, but for the present the important consideration is that W does not depend on the energy of the secondary electron, except at very low energies. The quantity W/e represents, therefore, a nearly constant energy absorption per roentgen for all photon energies.

Since the value of W for air is approximately 32.5 ev, or $32.5 \times e/300$ ergs, the value of W/e is 32.5/300 ergs. Converting this to ergs per gram of air, we have:

$$\text{Energy absorption per roentgen in 1 gm of air} = \frac{32.5}{300 \times 0.001293} = 83.8 \text{ ergs} \tag{3}$$

The "constant" thus calculated is the numerical value of the gram-roentgen. Values from 83 to 85 ergs/gm-r appear in the literature because values of W in the range 32.2 to 33 ev have been taken variously by different authors. Although the precise value of W is not yet settled (40) (see Section V-F and Table III of the Appendix), the energy absorption per gram-roentgen is known with sufficient accuracy for our present purpose and is also known to be nearly invariant with electron energy and therefore with radiation quality. It is the key figure in the interpretation of the roentgen either as energy flux or as energy absorption in tissue, although for both purposes it is also necessary to know the quantum energy of the radiation.

B. Energy Flux in Air for Given Quantum Energy

Since the roentgen implies a fixed energy absorption of about 84 ergs/gm of air, the quantity of radiation (time integral of the radiation intensity) giving rise to this absorption can be calculated if the air-absorption coefficients of the radiation are known. These are readily obtained from available theoretical and experimental data if the quantum energy of the radiation is given (see Chapter 2). Knowledge of the dose rate in roentgens per second and the quantum energy similarly enable the energy flux to be deduced. Calculations of energy flux per roentgen (57, 68) have been made, and more recently the problem of the high-energy region has been considered (23, 69, 83).

If the incident quantity of radiation, E_f (ergs/cm^2), is required to produce 1 r, the energy absorbed per gram of air will be $E_f\,(\mu_a/\rho)_{\text{air}}$ (ergs/gm), where $(\mu_a/\rho)_{\text{air}}$ is the true mass absorption coefficient for air (Chapter 2). From Eq. 3 it follows that

$$E_f\,(\mu_a/\rho)_{\text{air}} = 83.8 \text{ ergs/gm} \tag{4}$$

The true linear absorption coefficient, μ_a, is given by

$$\mu_a = \tau + \sigma_a + \kappa_a \tag{5}$$

where τ is the photoelectric absorption coefficient, σ_a the fraction of the photon energy imparted to the recoil electron in the Compton absorption process, and κ_a the fraction of the photon energy given to the positron and negatron in absorption by pair production. Mayneord (69) has calculated κ_a from the pair production coefficient, κ, by means of the expression:

$$\kappa_a = \frac{\kappa(h\nu - 1.02)}{h\nu} \tag{6}$$

where $h\nu$ is the photon energy in Mev. From Eqs. 4 and 5 the incident energy per square centimeter is then

$$E_f = \frac{83.8\rho}{\tau + \sigma_a + \kappa_a} \text{ ergs/cm}^2\text{-r} \tag{7}$$

Values of E_f are illustrated in Fig. 3 (and Chapter 2, Table VI) from which it is clear that the energy flux per roentgen varies in a complex manner with photon energy, increasing by some thirtyfold over the energy range 0.02 to 0.1 Mev, and then remaining almost constant at *ca* 3000 ergs/cm^2-r up to nearly 2 Mev. Great accurary is not claimed for the calculations at high energies because, apart from the difficulty in measuring radiation in roentgens at these energies, no account can easily be taken of the radiation energy loss of the secondary electrons which then occurs.

The results for radiations of energy up to a few Mev, however, are accurate within the limits set by our knowledge of W. If the methods described in Chapter 2 are used to derive the spectral distribution of dose in roentgens against photon energy for a heterogeneous beam, the photon spectrum, giving the number of photons per square centimeter per roentgen in each chosen energy interval, can be obtained from the data in Fig. 3. The spectra in Fig. 1 illustrate the results of typical calculations of this kind.

C. Energy absorption in Other Media

The energy absorption in a medium other than air, to which a dose of 1 r is given, can be calculated from the energy absorption per gram of air, provided that the absorption coefficients of the radiation in the medium and

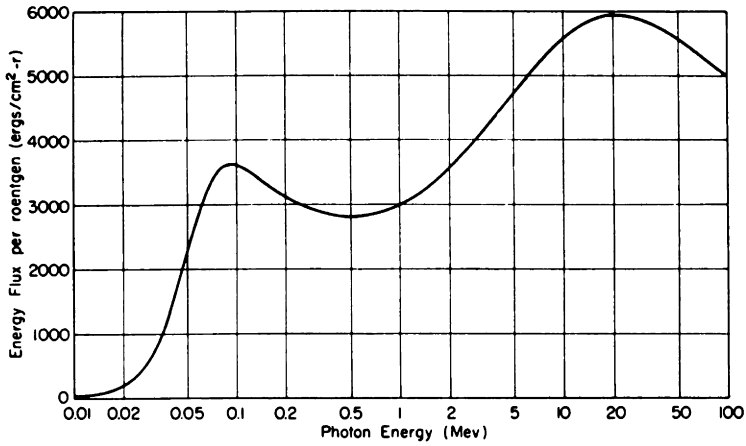

FIG. 3. Energy flux per roentgen (69). (W = 32.5 ev)

in air are accurately known. Calculations of energy absorption per roentgen in media of biological interest were made first by Mayneord (66) and subsequently by Spiers (80, 81) and Lea (59). Mayneord has since extended these calculations into the region of 1 to 100 Mev, although reservation is again necessary concerning the validity of the results at quantum energies greater than a few Mev. It will be shown in Section V that the energy imparted to a medium by radiation can be deduced from a measurement of the ionization in a small air-filled cavity within the medium, even at quantum energies where the meaning of a dose in roentgens becomes questionable. At present, however, attention will be confined to the deduction of energy absorption in different media for radiation qualities in the range where the roentgen is a valid unit.

If the true mass absorption coefficients of the medium and air are known, the energy absorption, E_M, per roentgen per gram of medium is given by

$$E_M = \frac{(\mu_a/\rho)_{\text{medium}}}{(\mu_a/\rho)_{\text{air}}} \times 83.8 \text{ ergs/gm-r} \tag{8}$$

For elements and simple chemical compounds the appropriate μ_a/ρ values can be obtained from Eqs. 5 and 6, although the calculations for numerous radiation qualities may be laborious (Chapter 2). For complex substances, such as body tissues, it may be preferable to work in terms of an "effective atomic number," $\bar{Z}$, using either a calculated value (66) or one found experimentally (80).

If a substance is composed of a fraction, p_1, by weight of element Z_1, p_2 of element Z_2, etc., its true mass absorption coefficient can be written

$$\mu_a/\rho = \frac{p_1 \mu_{a_1}}{\rho_1} + \frac{p_2 \mu_{a_2}}{\rho_2} + \cdots \tag{9}$$

The expressions τ, σ_a, and κ_a given in Eq. 5 for μ_a can be expanded in terms of Z_1, Z_2 $\cdots$ to give, in place of Eq. 9,

$$\mu_a/\rho = \frac{p_1\mathbf{N}}{A_1}(bZ_1^m\lambda^n + Z_1\,{}_e\sigma_a + cZ_1^2) + \frac{p_2\mathbf{N}}{A_2}(bZ_2^m\lambda^n + Z_2\,{}_e\sigma_a + cZ_2^2) + \cdots \quad (10)$$

where A = atomic number.
$\mathbf{N}$ = Avogadro's number.
λ^n gives the variation of τ with wavelength λ (value of $n \sim 3$).
m = exponent of Z in τ ($m \sim 4$).
b = empirical constant.
${}_e\sigma_a$ = true scatter-absorption coefficient per electron.
c = a constant defined in terms of the function used for ${}_e\kappa/Z$ at different photon energies.

Equation 10 can be rearranged, in terms of n_0, the number of electrons per gram in the substance, and α_1, α_2, $\cdots$, the fractional electron contents of elements Z_1, Z_2, $\cdots$, to give

$$\mu_a/\rho = n_0[b\lambda^n \sum(\alpha_1 Z_1^{m-1} + \cdots) + {}_e\sigma_a + c\sum(\alpha_1 Z_1 + \cdots)] \quad (11)$$

where

$$n_0 = \mathbf{N}\sum(p_1Z_1/A_1 + p_2Z_2/A_2 + \cdots) \quad (12)$$

and

$$\alpha_1 = \mathbf{N}p_1Z_1/n_0A_1 \quad (13)$$

with similar expressions for α_2, etc. Equation 11 shows that, in the region where photoelectric absorption is present and pair formation absent or negligible, an effective atomic number can be defined such that

$$\bar{Z}_\tau^{m-1} = \alpha_1 Z_1^{m-1} + \alpha_2 Z_2^{m-1} + \cdots \quad (14)$$

The expression for μ_a/ρ in terms of an effective atomic number may be expected to hold as long as a simple power function, $b\lambda^n Z^m$, is a sufficient approximation for the photoelectric absorption coefficient, that is, at photon energies well above the critical absorption energies of the atoms present in the irradiated material. It is not legitimate, however, as Hine (39) has pointed out, to carry over these values of $\bar{Z}$ into the expression for the pair formation coefficient. It is evident from Eq. 11 that the effective atomic number for pair formation is a linear function of Z_1, Z_2, $\cdots$, given by

$$\bar{Z}_\kappa = \alpha_1 Z_1 + \alpha_2 Z_2 + \cdots \quad (15)$$

No single definition of $\bar{Z}$ will satisfy Eq. 11; but it happens that for low atomic number materials of biological interest the photon energy ranges where τ and κ_a are respectively important do not overlap.

TABLE III

EFFECTIVE ATOMIC NUMBERS (46, 80)

Material	Density, gm/cm³	Number of electrons per gram (n_0)	$\bar{Z}_\tau$	$\bar{Z}_\kappa$
Air	0.001293	3.03×10^{23}	7.64	7.36
Water	1.00	3.34×10^{23}	7.42	6.60
Muscle	1.00	3.36×10^{23}	7.42	6.60
Subcutaneous fat	0.91	3.48×10^{23}	5.92	5.2
Bone	1.85	3.00×10^{23}	13.8	10.0

The expression for n_0 in Eq. 12 shows that this function depends on the ratios Z_1/A_1, etc. Since this ratio varies very slowly with atomic number, n_0 does not depend very much on composition, and it can usually be estimated with sufficient accuracy from the general nature of the atomic composition of the substance.

Table III gives data on n_0 and $\bar{Z}$ for a number of substances of interest, including tissues. The values of $\bar{Z}_\tau$ for tissues are experimentally determined (80), and the values of $\bar{Z}_\kappa$ are taken from calculations by Johns (46).

The energy absorption per gram-roentgen for a number of values of $\bar{Z}$ are shown in Fig. 4 (and Chapter 2, Fig. 21), where the curves for $\bar{Z}_\tau = 6.0$,

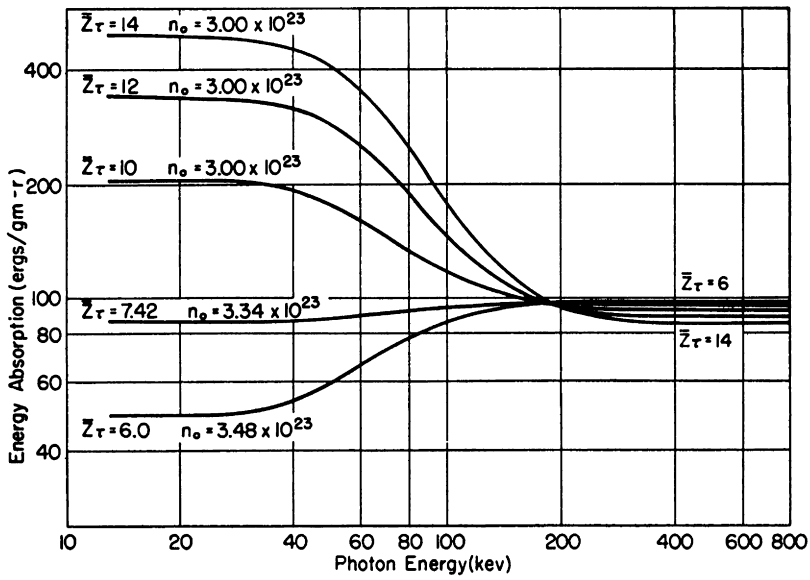

FIG. 4. Energy absorption in ergs per gram-roentgen as a function of photon energy for materials of different average atomic number $\bar{Z}_\tau$ (81a).

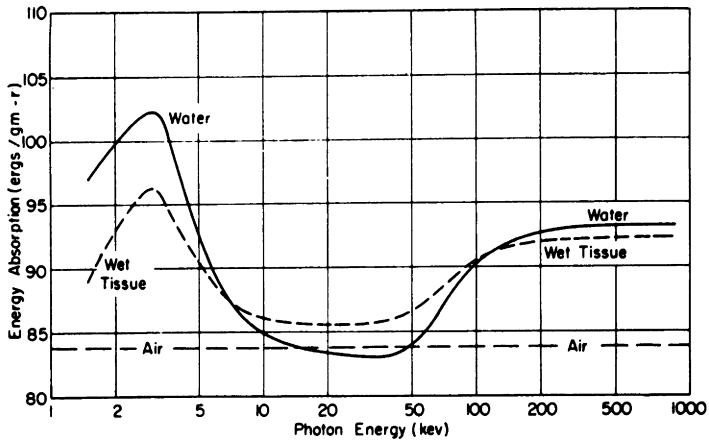

FIG. 5. Energy absorption in ergs per gram-roentgen in water and in wet tissue over the range 1 kev to 1 Mev photon energy (59).

7.4, and 14 correspond very nearly to those for subcutaneous fat, muscle, and hard bone. The approximate constancy of the energy absorption in muscle over this range of photon energies (0.01 to 1 Mev) is the feature which has justified the use of the roentgen as a unit of dose for therapeutic irradiation of the aqueous tissues of the body.

More detailed calculations (59) for the energy absorption in water and aqueous tissue are shown in Fig. 5. Greater variations are evident at photon energies below 0.01 Mev, but the energy absorption per gram-roentgen is still within $\pm 10\%$ of the value of 93 ergs/gm-r chosen for the energy value of the rep and the energy unit of Gray. The energy absorption in bone and fatty tissue together with that in air and water at photon energies greater than 1 Mev is shown in Fig. 21 of Chapter 2. Absorption by pair production which depends on Z^2 produces differences between the energy absorption in bone and aqueous tissues; but the effects are much less marked than in the region of photoelectric absorption, and the biological consequences in the irradiation of bone would not appear to be very significant.

The calculations discussed have been made for monoenergetic radiations. In translating them into practical cases, it may be necessary to use a mean photon energy deduced by methods considered in Section I-B. It is preferable, however, where energy absorption is to be considered in detail, to derive the energy absorption by summation over the whole photon spectrum. Further complications may exist where considerable amounts of scattered radiation are present and where the computation of energy absorption requires also a knowledge of the energies of the scattered quanta contributing to the dose (93).

IV. DETERMINATION OF DOSE IN ROENTGENS

A. Conditions of Ionization Current Measurement

The determination of dose in roentgens requires the measurement of an ionization current under saturation conditions (see Chapter 4). The field between the electrodes of the ionization chamber must be sufficient to collect all the ions without recombination, but not so high that the moving ions produce further ionization by collision processes. In air at atmospheric pressure, ionization by collision is unlikely at field strengths less than 3000 volts/cm, and for dose rates normally used in clinical and experimental work with x- and γ-rays saturation conditions are achieved with collecting field strengths below this level. At gas pressures greater than 1 atmosphere, however, and at high dose rates such as may occur in high-energy electron beams, saturation conditions may be difficult or impossible to attain. It is also difficult to obtain complete collection of all the ions produced by the tracks of densely ionizing particles such as protons and α-particles.

When saturation conditions do not hold, recombination may occur in two ways: (1) by "initial" or "columnar" recombination between ions along the track of the ionizing particle; (2) by "general" or "volume" recombination between ions from neighboring tracks. Columnar recombination depends on the density of ionization along the particle track and is not itself influenced by dose rate. Volume recombination, however, is dose-rate dependent, since the dose rate controls the number of tracks per unit volume. The relative importance of the two phenomena in relation to the efficiency of ion collection varies with the nature of the radiation, the dose rate, and the gas pressure in the ionization chamber. Thus, for atmospheric air ionized by x- or γ-rays, recombination is almost entirely due to volume recombination processes, for, with no collecting field and at dose rates of the order of 10^{-8} r/sec, not more than some 2% of the ions are lost by columnar recombination before the secondary electron tracks overlap by diffusion. With similar ionization rates produced by α-particles in atmospheric air, approximately half the ions will have recombined in their tracks before conditions for volume recombination set in, and even at high ionization rates of 100 esu/cm^3-min about 20% of the recombination is still due to columnar processes.

The theory of columnar recombination in a parallel-plate ionization chamber (42, 96) gives the following relation between the observed ionization current, i, and the saturation current, I:

$$\frac{1}{i} = \frac{1}{I} + \frac{\alpha N_0}{8\pi D I} f(x) \tag{16}$$

where α is the recombination coefficient, N_0 the number of ion pairs per

centimeter of track of the ionizing particle, D the diffusion coefficient, and $f(x)$ the following function of the Hankel cylindrical harmonic:

$$f(x) = e^{x} \frac{i\pi}{2} H_0^{(1)}(ix) \tag{17}$$

In this function $x = c(X/p)^2$, where X is the electric field strength, p the gas pressure, and c a constant which, for air, has the value 1.24×10^{-4}. Zanstra (96) has given curves from which $f(x)$ can be read for a range of x from 1 to 10^{-6} (see Chapter 4, Section II-B-6).

At any given pressure $\alpha N_0/8\pi DI$ is constant, and hence (from Eq. 16), if $1/i$ is plotted against $f(x)$ with the field strength, X, as the variable, the intercept at $f(x) = 0$ gives the value $1/I$. Provided a sufficient range of $f(x)$ can be obtained by varying X, the "Jaffé-Zanstra" plot enables I to be derived by extrapolation.

The effect of volume recombination on the measurement of pulsed radiation beams and of high continuous dose rates has been recently studied in detail (6–8) (see Chapter 4). For an instantaneous dose of r roentgens in a parallel-plate ionization chamber, having electrode spacing of d centimeters and collecting potential of V volts, Boag has shown that the fraction of ions collected is given by the Langevin (53) formula:

$$f(u) = \frac{1}{u} \ln (1 + u) \tag{18}$$

where, for air at 1 atmosphere, $u = 1090\ rd^2/V$. The function $f(u)$, from which the performance of a given chamber can be deduced, is shown in Fig. 12 of Chapter 4. If a parallel-plate ionization chamber is irradiated at a constant rate of q r/sec, the ratio of the ionization current to the saturation current is given by a function of $md^2\sqrt{q}/V$, where m is a constant characteristic of the gas at a given temperature and pressure (7). This relation is illustrated in Fig. 7 of Chapter 4, where the application of the results to ionization chamber design is considered in detail.

B. Parallel-Plate Ionization Chamber for Low- and Medium-Energy X-Rays

The apparatus used almost universally to measure x-ray dose in accordance with the definition of the roentgen is an adaptation of the parallel-plate ionization chamber. It is frequently termed a "free-air" or a "homogeneous" ionization chamber because the secondary electrons which produce the ionization originate and complete their tracks in the air of the chamber. By 1931 satisfactory agreement between the results of different national standardizing laboratories (Chapter 11) had been achieved for x-rays generated at 50 to 200 kv, and the principle of the parallel-plate apparatus will first be considered in relation to this energy range.

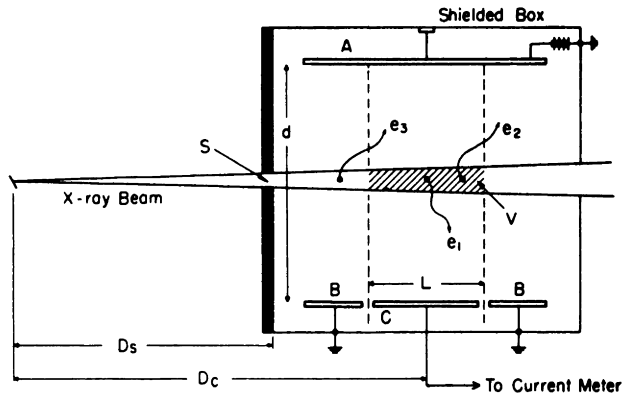

FIG. 6. Principle of parallel-plate free-air ionization chamber.

Some details of the design of a standard parallel-plate apparatus (20, 22, 48, 84) are illustrated in Fig. 6, where a narrow beam of x-rays is shown passing between the parallel plates A and B. A collecting electric field of the order of 50 to 100 volts/cm is applied between A and B, and the guard plates in electrode B define the field so that collection of ions is restricted to the space immediately between the area C and the high-voltage electrode, A. The separation of plates A and B must be sufficient to allow all the secondary electrons, e_1, e_2, etc., to complete their tracks in air, and conditions of electron equilibrium must hold. The ions lost owing to an electron such as e_2 leaving the collecting space on one side are then made up by the corresponding part of another track, e_3, entering from the other side. The ions collected are then effectively those arising from x-ray absorption in the mass of air enclosed by the volume shown shaded in Fig. 6, at a mean distance, D_e, from the source. Since attenuation of a beam of penetrating radiation follows the inverse square law, this volume of air is equivalent to the smaller volume, at distance D_s, given by the product of the area, S, of the diaphragm and the length, L, of the collecting electrode, C. This latter volume can be measured precisely, and furthermore the diaphragm, S, defines the position at which small ionization chambers can be placed for purposes of calibration. If the voltage change on the collecting electrode is V and the capacity of the measuring system is C esu, the dose in roentgens at the position of the diaphragm is

$$\text{Dose at position } S = \frac{CV}{300} \times \frac{1}{LS} \times \left(\frac{760}{p} \times \frac{273 + t}{273}\right) \text{ roentgens} \qquad (19)$$

where the expression in parentheses allows for the density of the air under the conditions of measurement.

Modification of the design of the parallel-plate ionization chamber is

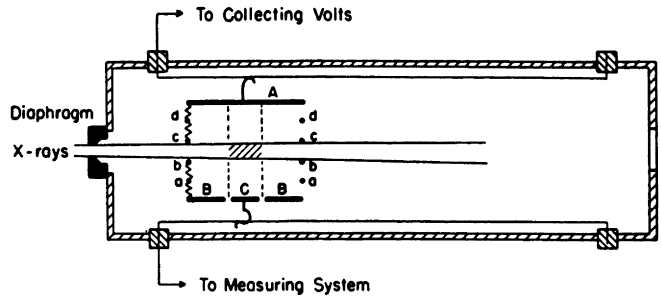

FIG. 7. Parallel-plate, free-air ionization chamber for low-voltage x-rays (88). The distance between the plate system AB and the diaphragm can be varied in order to determine corrections for air absorption.

necessary for the measurement of x-ray dose in the energy range below 50 kv. This is because appreciable x-ray absorption takes place between the diaphragm, S, and the measuring electrode, C. The chamber shown in Fig. 7 illustrates the method by which air absorption of soft radiation is minimized and appropriate corrections determined (88). The guard wires, a, b, c, and d, between plates A and B enable narrower guard plates, B, to be used to maintain the definition of the electric field at C and thus reduce the air path between the diaphragm and the collecting electrode, C. The whole electrode assembly can also be moved back from the diaphragm, thus making it possible to determine the air absorption correction, which for example may be as high as 3% per centimeter for radiation from an x-ray tube operated at 15 kv.

Further attention has been given by Kemp (50) to the geometry of free-air ionization chambers. The necessity for adequate spacing of plates A and B (Fig. 6) and for definition of the electric field at the edges of the collecting electrode, C, has already been explained. It is also necessary that the electric field at the lateral edge of the collecting electrode shall not be distorted if ions produced by secondary electrons traveling in that direction are to be collected without loss. Although this condition had been mentioned in recommendations of a number of standardizing laboratories (85), not all standard chambers have been adequately designed in this respect. The effective "collecting area" of a parallel-plate chamber (50) is illustrated by a cross-section perpendicular to the chamber length in Fig. 8. Adequate lateral dimensions of the collecting area were achieved for the electrode spacing (15-cm-wide electrodes at 12-cm spacing) used in this apparatus only by adding the guard wires at the sides of the electrodes. In one apparatus, hitherto used as a standard, ionization losses due to inadequate lateral geometry amount to 0.4% at 100 kv and to nearly 3% at 190 kv. (In Chapter 4, Section III-A, a more detailed discussion of the free-air ionization chamber is given.)

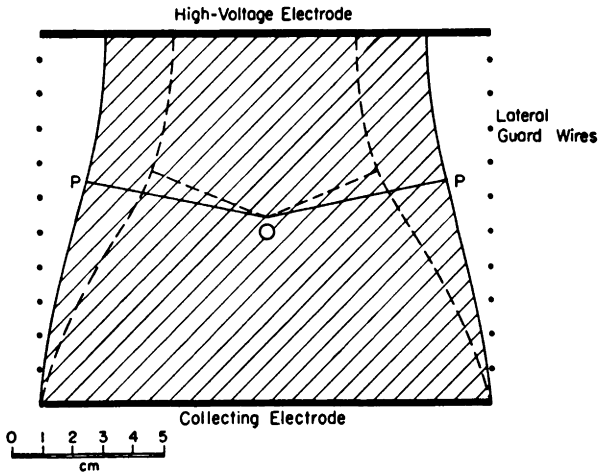

FIG. 8. Effective collecting area of a parallel-plate ionization chamber (50). The distance *OP* indicates the shortest distance which a secondary electron must travel to escape collection. The dotted lines represent diagrammatically the effect of omitting the lateral guard wires.

C. High-Pressure Parallel-Plate Chamber for High-Energy X- and γ-Rays

As the energy of the secondary electron rises with the energy of the x- or γ-ray quantum, it becomes increasingly difficult to construct an ionization chamber with a plate spacing adequate to secure the conditions for a homogeneous air chamber. A comprehensive discussion of this problem and of the experiences of earlier workers is given in a paper by Taylor *et al.* (86). These authors also describe a parallel-plate chamber in which both the plate separation and the air pressure can be varied. Typical results at a pressure of 1 atmosphere are given in Fig. 9, from which it is evident that adequate plate separation is achieved only for radiations generated at potentials up to 360 kv. At a pressure of 2 atmospheres a plate separation of some 25 cm was adequate for the measurement of 400-kv x-rays and a saturation ionization current was obtained with a collecting field of the order of 100 volts/cm.

The problem of measuring radiation dose in the range 0.5 to 2 Mev is illustrated by the attempts to measure the specific γ-ray dose rate from a radium source. A large free-air chamber of the guarded-field type and a plate separation of 3 meters at atmospheric pressure has been used for the determination of the specific γ-ray dose rate of radium (49). A large distance, of the order of 7 meters, was also necessary to ensure electron equilibrium in the forward direction. Such large distances obviously involved severe experimental difficulties.

A pressure of 10 atmospheres has been used for the measurement of

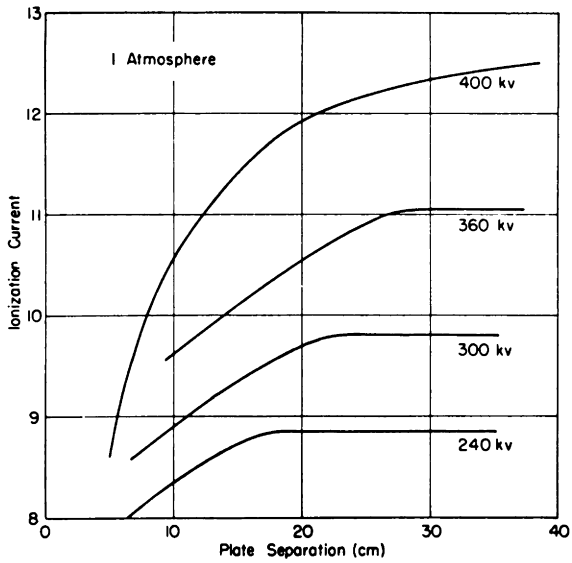

FIG. 9. Variation of ionization current with plate separation in a parallel-plate chamber operated at 1 atmosphere pressure (86).

radium γ-rays (87). A plate spacing of 35 cm was shown to be adequate (equivalent to 3.5 meters in atmospheric air), and the true saturation currents were derived by Jaffé-Zanstra extrapolation. The value of the γ-ray dose rate at 1 cm from 1 mg of radium, filtered by 0.5 mm Pt, was determined by Kaye and Binks (49) as 8.0 r/hr and is slightly low, probably because of inadequate geometry. The value of 8.26 r/hr obtained by Attix and Ritz* stands today as the most reliable determination of that constant, and recent revision of the results obtained with cavity ionization chambers gives an almost identical value (see Chapter 11, Section I-C).

V. THE BRAGG-GRAY THEORY OF THE SMALL IONIZATION CHAMBER

A. Statement of Fundamental Theory

In the free-air ionization chamber the quantum absorption and the subsequent energy dissipation by the secondary electrons both take place in the same gaseous medium. The chamber may be said to be "homogeneous," and the energy absorption in air may be derived from the ionization with an accuracy which is limited chiefly by our knowledge of the exact value of W (see Sections III-A and V-F) and by the degree to which that quantity is dependent on electron energy. In a "thimble" ionization chamber the conditions are different, since the walls of the chamber are irradiated and the ionization of the gas is due to electrons arising from quantum absorption both in the walls and in the gas filling. A homogeneous "air-wall' cham-

* *J. Research Nat. Bur. Standards* **59**, 293 (1957).

ber is not practicable, for there is no solid with the same atomic composition as atmospheric air. Composite materials (usually carbon with an admixture of elements of atomic number greater than that of oxygen) may be devised to give mass absorption coefficients equal to those for air over a range of quantum energies, but their electron stopping powers and the energy spectra of the secondary electrons will not necessarily match those of air. Homogeneous chambers having gas and chamber walls of identical molecular composition, such as a polyethylene chamber filled with ethylene, are practicable and have been used with success in problems of neutron and γ-ray dosimetry. If, however, the ionization chamber is sufficiently small and its wall thickness is greater than the range of the secondary electrons, a relationship can be derived between the true quantum energy absorption in the wall material and the ionization in the air or other gas filling of the chamber. As long as the conditions necessary for its validity are fulfilled, this relationship provides a method of measuring the energy deposition in a solid medium which is not limited to those radiations for which the roentgen is an acceptable unit. The method is also more sensitive, for example, than the calorimetric methods yet available.

As early as 1912, Bragg (10) related the ionization in a chamber irradiated with γ-rays to the electron stopping power of the wall materials, and the later, and independent, formulation of this theory by Gray (28, 29) is the basis of the now familiar Bragg-Gray principle. Gray considered the case of a solid medium traversed by secondary electrons and showed that the introduction of a small gas-filled cavity would not disturb the angular or energy distribution of secondary electrons at the position of the cavity, provided the dimensions of the cavity were such that the electrons lose only a small fraction of their energy in traversing it. The ratio of the energy lost by an electron in traversing unit mass per square centimeter of medium to that lost per unit mass per square centimeter of gas is equal to the ratio of the mass stopping powers of the medium and gas. It then follows that, if E_M is the energy imparted by the electrons to unit mass of the medium and E_G that imparted to unit mass of gas,

$$E_M = \frac{S_M}{S_G} E_G \tag{20}$$

where S_M and S_G are the mass stopping powers, respectively, of the medium and gas. The energy E_G results in ionization of the gas, and its value in Eq. 20 can be replaced by $J_G W$, where J_G is the number of ion pairs formed per unit mass of gas and W is the mean energy expended in the production of a pair of ions in the gas. If $\dot{\rho}_M$ is written for the ratio S_M/S_G, Eq. 20 becomes

$$E_M = J_G \rho_M W \tag{21}$$

Except under certain conditions to be discussed later, E_M, the energy im-

parted to the medium by the secondary electrons, is equal to the true energy absorption of the quantum radiation in the medium. Measurement of J_G and knowledge of ρ_M and W then determine the absorbed dose in the medium as understood in the definition of the rad. With appropriate modifications in the values of ρ_M and W, Eq. 21 can also be used for ionizing particles other than secondary electrons, although it may not be easy in every case to make a cavity ionization chamber small enough to satisfy the conditions of the theory.

Before further elaboration of the theory, the basic conditions for its validity may be summarized as follows:

1. The cavity must have dimensions such that only a very small fraction of the particle energy is dissipated in it. This means also that only a very small fraction of the particles contributing to the ionization will enter the cavity with a range smaller than the cavity dimensions.

2. Direct absorption of quantum radiation by the gas in the cavity should contribute only a negligible proportion of the total ionization—a requirement usually satisfied if the cavity complies with the first criterion.

3. The cavity must be surrounded by an "equilibrium thickness" of the solid medium so that all particles crossing it originate in the medium. The required thickness for electronic equilibrium is theoretically equal to the range of the particle of maximum energy released in the medium, although in practice path obliquity leads to the approximate establishment of electronic equilibrium at a wall thickness considerably less than the maximum range.

4. The energy dissipation by the ionizing particles must be sensibly uniform over the volume of the medium immediately surrounding the cavity and contributing to the electronic equilibrium. This implies that a source of quantum radiation must be sufficiently far from the cavity for the divergence of the beam to be negligible over the cavity dimensions. Attenuation of the quantum radiation by absorption in the medium will be negligible over distances of the order of the cavity dimensions if criterion 1 is fulfilled.

Conditions 1 to 4 are generally necessary if energy absorption per gram is to be determined unambiguously at a depth at which electronic equilibrium is complete. They are similarly required if energy absorption in a medium is to be used to determine radiation flux. The cavity chamber can still be employed, however, to measure energy absorption in situations such as those near the surface of a medium, where electronic equilibrium is being built up with depth below the surface. Conditions 1 and 2 must of course be fulfilled, but the chamber dimensions must now be small compared with the distance over which the build-up takes place, i.e., small compared with the particle range *in the medium.*

Apart from measurements in regions of partial electronic equilibrium, it

is found in practice that chambers having air volumes 1 or 2 cm in diameter fulfill the Bragg-Gray principle satisfactorily for the dosimetry of γ-rays of energies greater than about 1 Mev. Care must be taken, however, to ensure that these comparatively large chambers are not used in circumstances in which condition 4 is not satisfied. Some investigations (67, 79) illustrate the magnitude of divergence errors when the source distance is of the same order as the chamber dimensions. At radiation energies much below 1 Mev it is difficult to construct a chamber sufficiently small to meet theoretical requirements with a gas at atmospheric pressure. If, however, the gas pressure is lowered, chambers having internal dimensions of a few millimeters can be used for x-rays in the 100- to 200-kv region (14, 31). If the wall electrons lose only a very small fraction of their energy in crossing the chamber gas, it follows that the observed ionization will be proportional to the gas pressure. The behavior of a chamber with respect to conditions 1 and 2 can be tested, therefore, by studies of ionization *vs* gas pressure. At extremely low pressures, however, additional current appears, not because of ionization of the air, but because of the emission of slow electrons from the chamber wall, which can migrate from one electrode to another under the influence of the collecting field (37, 76, 88, 94).

At the lower quantum energies, absolute radiation dosimetry can be based on the parallel-plate ionization chambers of the national standardizing laboratories. For corpuscular radiations and for quantum radiations of energies greater than 1 Mev, however, the cavity ionization chamber provides the method most widely used for the measurement of radiation dose, and in recent years considerable attention has been given to the experimental study and theoretical refinement of the Bragg-Gray formula.

B. Elaboration of the Cavity Ionization Chamber Theory

Development of the Bragg-Gray theory to express a relationship between ionization and the flux of various types of radiation has been undertaken by a number of investigators (16, 26, 27, 34, 56, 58, 90, 91). Whether the Bragg-Gray relationship is used for the measurement of the incident radiation flux or for the determination of energy deposition in a given medium, some modification of the simple basic expression is required. Although space does not allow a review in detail of all the work done recently in a subject which is still under considerable discussion, some attempt will be made to illustrate the nature of the refinements being considered.

It was recognized at an early date that, of the factors ρ_M and W in Eq. 21, ρ_M depended on the atomic numbers of the medium and the gas and on the particle energy, and W depended on the gas and possibly also, at very low energies, on particle energy. It appears likely, however, that in the measurement of high-energy γ-radiations the variation of W with electron

energy will not be very important and that for these purposes W can be regarded as constant.

For electrons the factor ρ_M can be expressed as

$$\rho_M = \frac{n_M {}_eS_M}{n_G {}_eS_G} \tag{22}$$

where n_M and n_G are the numbers of electrons per gram and ${}_eS_M$ and ${}_eS_G$ are the stopping powers, $(dT/dx)_M$ and $(dT/dx)_G$, per electron, respectively, for the medium and the gas. Since ${}_eS_M$ and ${}_eS_G$ depend on the energy of the electron, and the electrons traversing the gas cavity have a wide distribution of energies, some means must be used to derive an average value of ${}_eS_M/{}_eS_G$ appropriate to the secondary electron energies produced by any given radiation. The discussion of this problem will be in terms of the secondary electrons arising from the absorption of quantum radiation, but it will be evident that similar considerations hold when the cavity chamber theory is applied to the dosimetry of corpuscular radiations. Before consideration of the ways in which mean values of ${}_eS_M/{}_eS_G$ have been derived it is first necessary to discuss the calculation of this ratio for an instantaneous electron energy.

C. Calculation of Stopping Powers

The electron stopping powers, ${}_eS_M$ and ${}_eS_G$, have been calculated usually by means of the Bethe-Bloch formulas for the energy loss of β-particles in passing through matter, but changes in the values used by different authors have come about as increased knowledge of collision processes and the required experimental constants have improved the accuracy of calculation. The calculation of the stopping power per electron, ${}_eS$, for a given element, can be discussed (see Chapter 2, Eq. 40) in terms of the following expression (3, 70):

$$\begin{aligned} {}_eS = \frac{2\pi e^4}{m_0 c^2 \beta^2}\Bigg[\ln \frac{m_0 c^2 \beta^2 T}{2I^2(1-\beta^2)} + (1-\beta^2) \\ - (2\sqrt{1-\beta^2} - 1 + \beta^2)\ln 2 + \tfrac{1}{8}(1-\sqrt{1-\beta^2})^2 - \delta\Bigg] \end{aligned} \tag{23}$$

where e, m_0, c, and β have their usual significance, I is the average excitation potential of the atom, and T is the kinetic energy of the incident electron. The function inside the brackets varies slowly with particle energy, and hence ${}_eS$ at first decreases as the electron velocity, βc, increases. The term preceding the brackets becomes constant as $\beta \to 1$, and ${}_eS$ reaches a broad minimum, in the electron energy range 2 to 5 Mev, increasing beyond this point as the logarithmic function increases with electron energy, T (see Chapter 2, Figs. 22 and 23). The first term in the brackets represents

the early solution for nonrelativistic velocities, and the next three terms the modifications necessary for relativistic velocities. The more recent developments concern the values for I and for δ, a correction term which has been included in Eq. 23.

The stopping power formula, which is derived for a simple hydrogen-like atom, can be applied to other electronic configurations if an average excitation potential, I, can be determined. This has been done empirically by adjusting I to fit known energy-range data, and for this purpose α-ray data, having greater accuracy than similar β-ray data, have been used. Thus Bethe (60) chose a value of $I = 80.5$ ev for air so that the difference between the ranges of the ThC′ long-range α-particle and the Po α-particle, calculated by the stopping power formula, agreed with experiment. The use of α-particle stopping powers of other materials relative to air enabled the values of I for other elements to be estimated (62). A general, but admittedly approximate, relationship ($I = 13.5Z$) has been used as a basis for stopping power calculations by numerous investigators. In their studies of the Bragg-Gray theory, for example, Laurence (56) and Cormack and Johns (16) have used values of I calculated by this expression.

In recent years range-energy relations have been investigated for protons and α-particles at the very high energies attainable with particle accelerators. Measurements of energy loss by protons of 300-Mev energy have been used to determine average excitation potentials of a number of elements under the relativistic velocity conditions which, in the case of electrons, occur at the lower energies of a few Mev. In this way, Mather and Segrè (65) confirmed the value of I of 150 ev for aluminum found earlier by Wilson (95) using particles of lower energy and the experimental values of I given in Table IV have been deduced (4) from measurements with 340 Mev protons (2). Values of I for a number of compounds, calculated by interpolation from the values for the elements, are also included in Table IV, together with Bethe and Livingstone's value for air, which agrees well with recent measurements (9).

The term δ in Eq. 23 is a correction to allow for the effect of the condensed state on stopping power. If atoms are closely packed, as in a condensed system, polarization of the medium by the field of the charged particle effectively reduces the stopping power (see Chapter 2, Section II-B). Quantitative calculations of this reduction were made by several authors (25, 38, 92). Recent calculations (82) of the stopping power of gases and solids of possible concern in radiation dosimetry are based on average excitation potentials deduced from recent experimental data and, where necessary, include corrections for the finite-energy density effect in condensed media. Values of electron stopping powers as a function of the instantaneous electron energy are given in Chapter 2, Section II-B.

TABLE IV

AVERAGE EXCITATION POTENTIALS (I)

Material	I, ev
Experimental Values:	
Hydrogen	15.6
Lithium	34.0
Beryllium	60.4
Carbon	76.4
Aluminum	150
Iron	241
Copper	276
Silver	418
Tin	463
Tungsten	655
Lead	705
Uranium	811
Air	80.5
Interpolated Values:	
Helium	26.9
Nitrogen	87.7
Argon	192
Oxygen	98
Calculated Values:	
Water	68.0
Anthracene	64.6
Polyethylene	51.4
Polystyrene	60.5
Lucite	65.4
Bakelite	68.8

D. Effective Stopping Power Ratio

From his original study of the ionization produced by radium γ-rays in small air-filled chambers, Gray (28, 29) deduced the effective stopping powers relative to air of a number of solids from beryllium to copper. Gray's results, illustrated in Fig. 10, are, therefore, mean values of the ratio ${}_eS_M/{}_eS_G$, averaged experimentally over the energy spectrum of the secondary electrons released by the γ-rays of RaB and RaC. In the general case when both ρ_M and W are considered to vary with electron energy, an average value of $\rho_M W$ must be used, defined (34), for example, as

$$\frac{1}{\overline{\rho_M W}} = \frac{\int_0^T \frac{f(Q)}{Q} \int_0^Q \frac{dQ\,dE}{\rho_M(E)W(E)}}{\int_0^T f(Q)\,dQ} \tag{24}$$

where the number of electrons having energies within the range Q to $Q +$

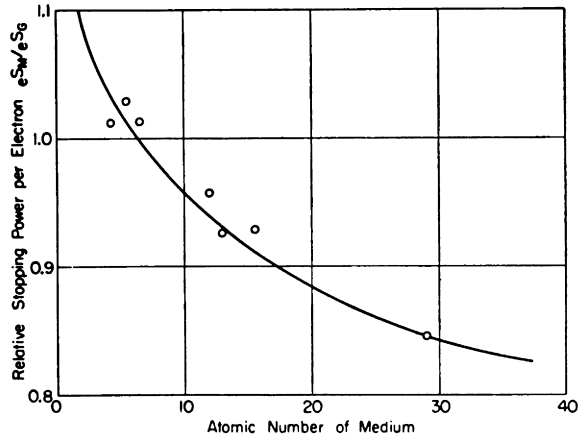

FIG. 10. Relative stopping power per electron for the energy spectrum of the secondary electrons released by RaB and RaC γ-rays (28, 29, 34).

dQ is $f(Q)\,dQ$, and $\rho_M(E)$ and $W(E)$ are the values of ρ_M and W for an electron of instantaneous energy, E. The integral

$$\frac{1}{Q}\int_0^Q dE/\rho_M(E)W(E)$$

gives the value of $[\rho_M(E)W(E)]^{-1}$ averaged over all energies assumed by an electron of initial energy Q, and this mean is averaged over all energies of secondary electrons released from zero to a maximum energy, T. If W can be regarded as invariant with electron energy, it can be omitted from the integration, and Eq. 24 then gives the effective value of $1/\rho_M$ averaged over all speeds of particle entering the air cavity.

Laurence (56) corrected for the wall effect in small ionization chamber measurements by replacing ${}_eS_G/{}_eS_M$ in Gray's original discussion by a function B, relating the ionization in a chamber of wall, Z_w, to that in an air-wall chamber:

$$B = 1 + \left(2\log\frac{Z_w}{Z_a}\right)\frac{J}{L} + \left(2\log\frac{Z_w}{Z_a}\right)^2\frac{K}{L} + \cdots \qquad (25)$$

where J/L is a function essentially similar to that in Eq. 24 averaging $1/{}_eS$ over the electron energy spectrum, and K/L similarly averages a second, smaller term, $1/{}_eS^2$, ${}_eS$ being the electron stopping power for air. The functions J, K, and L are calculated by Laurence for conditions under which quantum absorption by the Compton process alone takes place. Recently Whyte (91) has revised Laurence's values of B by including corrections for the polarization effect in condensed media and using the values

TABLE V

VALUES OF FUNCTION B FOR SEVERAL γ-RAY EMITTERS (91)*

Wall material	Radiation				
	I^{131}	Au^{198}	Co^{60}	Ra (B and C) (0.5 mm Pt)	Na^{24}
Graphite	0.993	0.993	0.998	0.999	1.008
Polystyrene	0.961	0.962	0.971	0.971	0.983
Lucite	0.970	0.971	0.978	0.979	0.988
Bakelite	0.977	0.978	0.985	0.985	0.995
Aluminum	1.101	1.100	1.084	1.086	1.081

* B is defined by Eq. 25.

given in Table IV for the average excitation potentials. Revised values of B are given in Table V for a number of commonly used γ-radiations.

Cormack and Johns (16) have applied the Bragg-Gray principle to the measurement of the energy flux of radiations in the quantum range 1 to 20 Mev and in doing so have also derived mean values of ${}_eS_G/{}_eS_M$. As in the method indicated by Eq. 24, an average stopping power ratio is found over the energies associated with an electron of initial energy E_i by the following expression:

$$\bar{Q}(E_i) = \frac{1}{E_i}\int_0^{E_i} \frac{{}_eS_G}{{}_eS_M}\,dE \tag{26}$$

The quantity $\bar{Q}(E_i)$ is then weighted by a factor $N(E_i)E_i$ and averaged over all initial electron energies, giving a value $\bar{\bar{Q}}(h\nu)$:

$$\bar{\bar{Q}}(h\nu) = \frac{\int_0^{E_{i(\max)}} N(E_i)E_i\bar{Q}(E_i)\,dE_i}{\int_0^{E_{i(\max)}} N(E_i)E_i\,dE_i} \tag{27}$$

The method of averaging has more justification than that in Eq. 24 in that the weighting factor used is the energy contribution, $N(E_i)E_i\,dE_i$, instead of the numbers of electrons, $N(E_i)\,dE_i$. At the electron energies considered by Cormack and Johns (0.05 Mev upward) the ratios ${}_eS_G/{}_eS_M$ vary slowly with energy, and there is little difference between the two methods of averaging. Since radiative energy losses become important for electrons of high energy, however, and only collision losses can contribute to ionization of the gas, ${}_eS_G$ in Eq. 26 refers to collision losses only, whereas ${}_eS_M$ is the total energy loss, including that by radiation. Cormack and Johns used the

Bethe-Bloch formula for collision losses without density-effect corrections and with mean excitation potentials given by $13.5Z$. Their values of $\bar{Q}(h\nu)$ cannot be compared directly, therefore, with the values of B given by Whyte (91). At quantum energies of about 1 Mev, where radiative losses are small, the values for light elements are 1 to 2 % lower than the corresponding values given by Whyte and would appear to be very near to the original values of B calculated by Laurence (56).

A study by Burch (12) of a more rigorous formulation of the Bragg-Gray principle suggests that the energy deposition by an electron in crossing the air cavity (or a corresponding mass of solid medium) is not identical with the total collision energy loss, since, in δ-track formation, some of the more energetic δ-tracks will carry energy out of the air volume or solid element concerned. In place of the mass stopping power ratio, S_M/S_G, of Eq. 20, a ratio of the "mass energy deposition" is used, defined by

$$R_E = \frac{\rho_G\,(dE/dx)_M}{\rho_M\,(dE/dx)_G} \tag{28}$$

where dE/dx is the energy deposition per unit length of track in a medium of density ρ. The extent to which dE/dx falls, by δ-track escape, below the total collision energy loss depends on the size and shape of the cavity, since this sets the upper limit, η, to the energy of the δ-track which remains within the cavity or solid element. R_E is calculated, therefore, from the stopping power formulas by using appropriate values of η_M and η_G for the upper limit of collision energy transfer. In the "distant collision" formula (used in place of Eq. 23), for example, η would replace $T/2$, which represents the maximum possible energy transfer. The "δ term" is included for the condensed medium, M, but omitted for the gas phase, G. The mean value of R (corresponding to $\bar{\rho}_M$ in Gray's Eq. 21) averaged over all the electrons crossing the air cavity is reduced to

$$\bar{R} = \frac{\int_0^T R_E\,(\Delta y)_E\,N_E\,dE}{\int_0^T (\Delta y)_E\,N_E\,dE} \tag{29}$$

where $N_E\,dE$ is the number of electrons in the medium in the region of the cavity with energies in the range E to $E + dE$, and $(\Delta y)_E$ is the average distance between the entry and exit points of an electron of energy E in crossing the cavity. The distance $(\Delta y)_E$ in the weighting factor in Eq. 29 depends on cavity shape as well as on the electron energy, since the distribution of electrons is not isotropic. Only in the case of a spherical cavity is $(\Delta y)_E$ the same for electrons of all energies.

Spencer and Attix (77) have produced a theory of cavity ionization restating the Bragg-Gray relation in a form giving the energy dissipation in

an air cavity surrounded by wall material, Z, as

$$JW = H_z(T_0, \Delta) = \int_{\Delta}^{T_0} I_z(T_0, T)\, S_{\text{air}}(T, \Delta)\, dT \qquad (30)$$

where $I_z(T_0, T)\, dT$ is the number of electrons in the medium, Z, having energies between T and $T + dT$ and arising from primary electrons of initial energy T_0 (see next section). The parameter, Δ, is an energy of the order required by an electron to cross the air cavity and is intended to take into account the effect of cavity size. The stopping power, $S_{\text{air}}(T, \Delta)$, includes only energy losses less than an amount Δ, and the integral is taken over electron energies greater than Δ, i.e., over the spectrum of electrons capable of crossing the air cavity. Calculations of the energy dissipation function, $H_z(T_0, \Delta)$, were made for a number of wall materials from carbon to lead, for a range of Δ from approximately 0.6 to 20 kev, and for γ-ray energies between 0.3 and 1.3 Mev. The cavity sizes corresponding to the values chosen for Δ vary from about 5 mm at 20 kev to 0.02 mm at 0.6 kev for chambers operated at 1 atmosphere, or, in the latter case, to a 5-mm chamber at a pressure of about 2 mm of mercury. A function $f_z(\Delta)$ is derived, replacing the stopping power ratio, ρ_M, in Eq. 21. This is shown to vary slowly with Δ for ionization chambers made of light elements and having linear dimensions of a few millimeters. For heavy elements, however, the theory shows that $f_z(\Delta)$ depends on Δ and increases appreciably as the cavity dimensions are reduced below a spacing of about 2 mm of atmospheric air—a feature borne out by early measurements (28) of the ionization per unit mass of air in a very small lead chamber as the pressure is reduced from 1 atmosphere to 200 mm of mercury.

Although the refinements of the Bragg-Gray theory considered in this section are themselves approximations to the solution of an inherently complex problem, cavity ionization can be used to determine energy absorption in light atom media with an accuracy approaching 1 or 2%. Thus the ratio of the ionization produced by Co^{60} γ-rays in a carbon chamber to that in a free air chamber is calculated to be 0.998 by Whyte (91) and 1.007 by Burch (12). The latter figure is for a 2-cm spherical chamber. The ratio of the ionization in aluminum and carbon chambers for the same radiation has been given as 1.086 by Whyte, 1.096 by Cormack and Johns (16) (but corrected by the writer to the same I values as used by Whyte), and 1.11 by Spencer and Attix (77) (for a 5-mm chamber). These ratios compare with recent experimental values of 1.08 $\pm$ 0.01 by Cormack and Johns and 1.10 by Attix and De La Vergne (1). Similarly the Al/C ratio for the 0.41-Mev γ-radiation of Au^{198}, calculated by Whyte as 1.107 and by Spencer and Attix as 1.14, compares with Attix and De La Vergne's measured value of 1.14.

For wall materials of high atomic number, however, the situation is much